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Model for Blanching Potatoes and other Vegetables

M. F. Kozempel, J. F. Sullivan, and J. C. Craig, Jr.

Eastern Regional Research Center*,
Philadelphia, Pennsylvania 19118 (U.S.A.)

A mathematical model to simulate the precooking or blanching of potatoes was developed. The model describes the diffusion of soluble solids, glucose, potassium, magnesium, and phosphorus to account for the mass transfer from the potato to the blanch water. Although the model was developed for 0.95 cm French fry cut potatoes, it is applicable to other type and size cuts and other vegetables.

Introduction

Current concerns for energy, waste treatment, and nutrition have prompted us to undertake the development of a process simulator for vegetable processing. Although simulators are available for application to refining, chemical, and petrochemical processing, they are largely not applicable to food processing because the physical data and models have not been developed. As a first step in developing a simulator for food processing, hot water blanching of vegetables was studied. Potatoes make up the leading processed vegetable crop (1). Since the instant potato flake process was originally developed at this laboratory (2), we began our study using the flake process in which a critical unit operation is blanching, or precooking.

Almost any reasonably sized cut of potatoes is suitable for the production of flakes-slabs, dice, French fries, or even slivers. The major outlet for processed potatoes is French fries, which must also be blanched. Therefore, a 0.95 cm French fry cut was chosen to study the potato flake process.

Hot blanch water leaches solids from vegetables. YANG and BRIER showed that diffusion is the rate controlling step in leaching beets (3). However, they employed a graphical solution. SWARTZ and CARROAD (4) published data on the leaching of several vegetables including lima beans and broccoli. In undertaking a similar experimental study with potatoes, our objective was to develop a purely mathematical model specific for potatoes but sufficiently general to apply to other commodities.

Experimental

Blanching was simulated on a small pilot plant scale. An appropriate model was developed to correlate the data and the predictability of the model was checked. Most of the studies were made on the equipment shown in **Fig. 1.** Water was fed to a surge tank at a controlled rate. A steam heated exchanger controlled the temperature of the water fed to the blanch tank to maintain the blanch water at 77 °C. The outlet water rate was adjusted to be equal to the feed water input rate. Various recycle streams were added using two Eastern centrifugal pumps, model D-11, to provide efficient mixing of all water in the system and maintain steady water levels in the blanch and surge tanks. The water temperature was monitored in the blanch tank. The system mass varied from run to run from 87 to 109 kg water.

French fry cuts, 0.95 cm, were processed in the precooker in perforated metal baskets, 48.25 cm × 6.4 cm × 15.25 cm. The precooker held five baskets. The flow rate was a function of the basket loading and the residence time. For example, a 7.6 kg/h feed rate was simulated by filling each basket with 507 g of potatoes and putting one basket in every 4 min. At 20 min the first basket came out and a new basket went in. The average flow rate was 7.6 kg/h and the residence time 20 min.

Maine Russet Burbank potatoes were used throughout this study except for two experiments with Idaho Russet Burbank potatoes. The processing steps preceding blanching were: lye-peeling @ 71 °C, trimming, sulfite rinse, cutting with an Urschel cutter, Model G-A, sulfite rinse, screening/washing, and sulfite rinse.

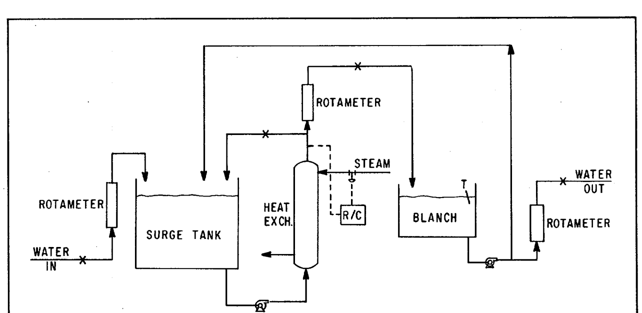

Fig. 1 Equipment for simulating precooking potatoes

*Agricultural Research, Science and Education Administration, U.S. Department of Agriculture.

Inlet and outlet water samples were collected and analyzed for soluble solids, glucose, potassium, magnesium, and phosphorus as follows:

Dissolved Solids
Liquid samples were evaporated on a steam bath to remove the bulk of water, then finally dried to a constant weight in air oven set at 105°C.

Moisture
Moisture content of potato was determined by AOAC method 7.003 (5).

Minerals
Potassium, magnesium, and calcium were determined directly on potato water samples acidified with HNO_3, in an Atomic Absorption Spectrophotometer, Perkin Elmer 306. Solid samples were either dry ashed or acid extracted (with HNO_3) under reflux for 12 h, filtered, diluted, and measured by atomic absorption sprectroscopy.

Glucose
Potatoes were extracted and analyzed as described by DELLAMONICA *et al.* (6). Potato water samples were analyzed with a YSI-Model 27 Industrial Sugar Analyzer, all analyzed within 4 h to minimize loss of the glucose.

Phosphorus
Phosphorus was determined by the method of FISKE and SUBBAROW (7).

Mathematical Model
YANG and BRIER (3) showed that the rate controlling step, at least in leaching beets, is diffusion within the vegetable. We assumed that diffusion is rate controlling in potatoes as well.
Considering the precooker as a well-stirred tank **(Fig. 2)** a mass rate balance was made as in Eqn 1:

In – Out = Accumulation

$$PMC_1 + WS_1 - PMC - WS = \frac{d(V\varrho S + PM\tau\bar{C})}{d\theta} = \frac{V\varrho dS}{d\theta} + PM\tau\frac{d}{d\theta}\left(\frac{C_1+C}{2}\right) \qquad \text{Eqn. [1]}$$

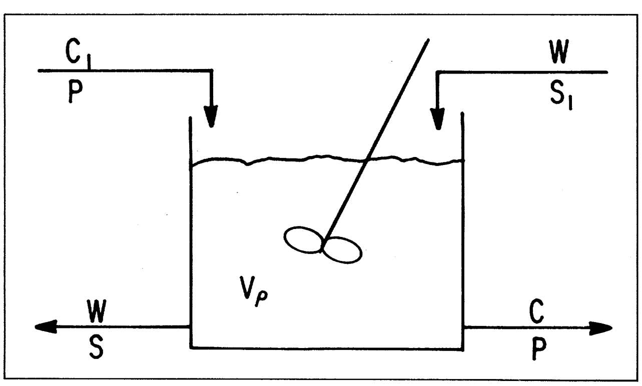

Fig. 2 Diagram of the precook for development of the model

The concentration in the potatoes in the bath varies from C_1 at the inlet to C at the outlet. On evaluation, the accumulation term involving $d\bar{C}/d\theta$ is substantially smaller, relative to the other accumulation term involving $dS/d\theta$. Therefore, we approximated $\bar{C}$ with the arithmetic average $(C_1 + C)/2$. We considered the French fry cut potato as a potato slab of thickness L. According to YANG and BRIER (3), the solute concentration due to diffusion for a solid slab of finite thickness L can be expressed as:

$$C = C_e + (C_1 - C_e)\frac{8}{\pi^2}\sum_{m=0}^{\infty}\frac{1}{(2m+1)^2}\exp[-D(2m+1)^2\pi^2\tau/L^2] \qquad \text{Eqn. [2]}$$

In our system only the first term of the series is significant and Eqn. [2] simplifies to Eqn. [3].

$$C = C_e + (C_1 - C_e)\frac{8}{\pi^2}\exp[-D\pi^2\tau/L^2] \qquad \text{Eqn. [3]}$$

(D is not exactly the diffusivity because L is a nominal dimension.)

The leaching driving force is the gradient between the solute concentration in the potato juice, C_1, and the solute concentration in the blanch water, S. The highest concentration the solute can reach is, C_1, the solute concentration in the juice of the feed potatoes. Theoretically, the solute concentration in the blanch water at equilibrium is equal to the solute concentration in the potato juice, and there is no driving force or net transfer of solute between the potato and the blanch water. Hence, the equilibrium solute concentration, C_e, can be equated to the solute concentration in the water, S:

$$C_e = S \qquad \text{Eqn. [4]}$$

Substituting Eqn. [4] into Eqn. [3] gives:

$$C = S + (C_1 - S)\frac{8}{\pi^2}\exp[-\pi^2 D\tau/L^2] \qquad \text{Eqn. [5]}$$

Now Eqn. [1] can be solved by using Eqn. [5] to replace C in Eqn. [1] with a function of S.

$$PMC_1 + WS_1 - PM\,[S + (C_1 - S)\frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)] - WS = \frac{V\varrho dS}{d\theta} + \frac{PM\tau}{2}\frac{d}{d\theta}[S + (C_1 - S)\frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)] \qquad \text{Eqn. [6]}$$

This can be rearranged to:

$$PMC_1\,[1 - \frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)] - PMS\,[1 - \frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)] + W(S_1 - S) = [V\varrho + \frac{PM\tau}{2}(1 - \frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2))]\frac{dS}{d\theta} \qquad \text{Eqn. [7]}$$

Eqn. [7] was integrated by use of the Runge-Kutta (8) approximation. At steady state $dS/d\theta = 0$ and Eqn. [7] becomes:

$$S = \frac{PMC_1\,[1 - \frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)] + WS_1}{PM\,[1 - \frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)] + W} \qquad \text{Eqn. [8]}$$

Results and Discussion

Processing of potatoes in the precooker was simulated at various potato and water rates and extraction times as listed in **Tab. 1. Fig. 3** is a plot of typical experimental data for potassium (K) concentration of the blanch water as a function of process time for four of these runs. Using the model previously derived, we correlated the data for runs 16 to 26 for K, Mg, P and soluble solids. To fit the model to the data, we had to determine the best values for D and C_1 (the value of C_1 cannot be measured analytically). We used a pattern optimization program to minimize the sum of squares of the

Tab. 1 Processing parameters for the blancher

Run No.	Potato Flow rate, kg/h	Water Flow rate, kg/h	Extraction time, h
15	13.6	0	.33
16	13.6	153.7	.33
17	13.6	81.2	.33
18	13.6	83.0	.33
21	13.6	35.4	.33
24	20.4	91.4	.33
25	8.8	45.5	.33
26	6.8	98.4	.67
27	13.6	86.3	.33
28	13.6	86.3	.33
29	13.6	86.3	.50

Tab. 2 Values of D and C_1 for each solute

Solute	D	C_1
K	0.423	0.00292
Mg	0.389	0.00015
P	0.389	0.00017
Soluble solids	0.274	0.0305
Glucose	4.057	*

*See discussion

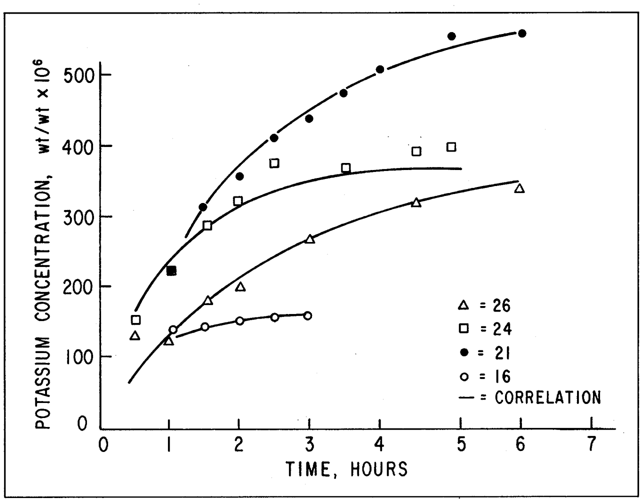

Fig. 3 Correlation of potassium concentration in precook water vs processing time for Maine Russet Burbank Potatoes, 0.95 cm French fry cuts, D = 0.423, runs 16, 21, 24, 26

error between experimental and calculated data points for each component. The correlation coefficients, R, for the runs in **Fig. 3** were 0.960, 0.964, 0.995 and 0.898. **Tab. 2** lists the values of D and C_1.

The model correlates the data within engineering accuracy. The next step was to determine if it can predict. We extrapolated the model to predict K and soluble solids concentration using Idaho Russet Burbank potatoes instead of Maine Russet Burbank potatoes–duplicate runs 27 and 28. The model predicted the K concentration accurately **(Fig. 4)** with R equal to 0.982. Prediction for soluble solids was somewhat disappointing **(Fig. 5)**; the R for run 27 was 0.913 but only 0.754 for run 28. Considering that these potatoes were from a different geographical area this is not too surprising. We would expect the potatoes to have a different composition of soluble solids affecting the value of C_1. We used the model to

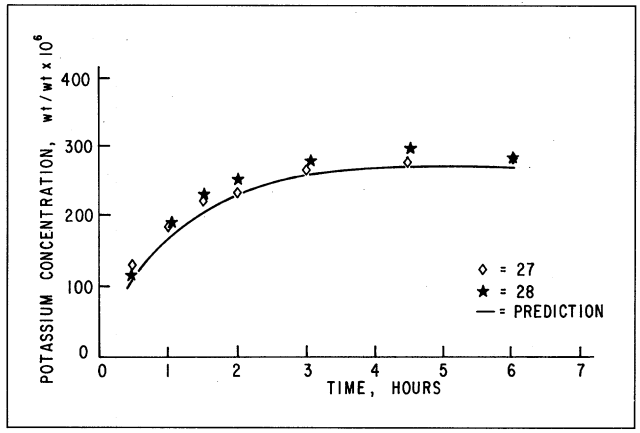

Fig. 4 Predicted concentration of potassium in precook water vs processing time for Idaho Russet Burbank Potatoes, 0.95 cm French fry cuts, D = 0.423, runs 27, 28

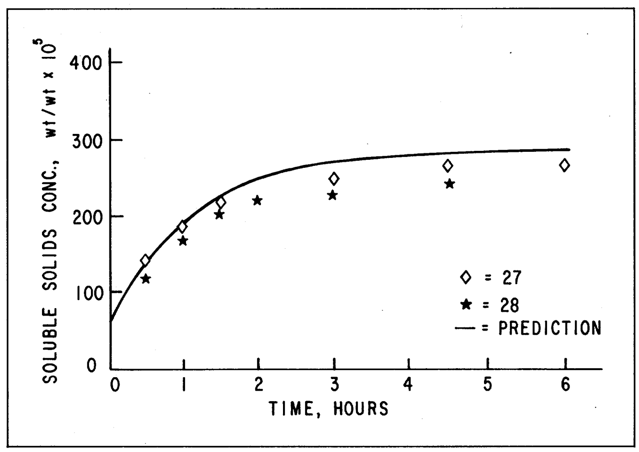

Fig. 5 Predicted concentration of soluble solids in precook water vs processing time for Idaho Russet Burbank Potatoes, 0.95 cm French fry cuts, D = 0.274, runs 27, 28

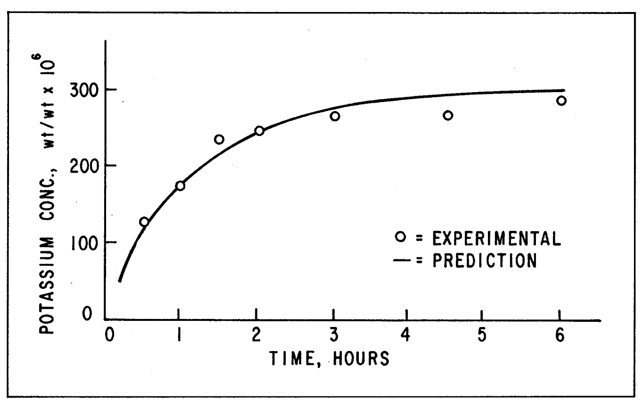

Fig. 6 Predicted concentration of potassium in precook water vs processing time for Maine Russet Burbank Potatoes, 0.95 cm French fry cuts, with a different extraction time, D = 0.423

predict the K concentration for run 29 in which we used Maine Russet Burbank potatoes and changed the extraction time **(Fig. 6).** The results are well within engineering accuracy with an R of 0.948.

Modeling the glucose concentration was somewhat more difficult. The glucose concentration of the raw potato changed during storage at 3.3 °C. Since C_1 is a measure of the leachable solute concentration in the raw potato, C_1 for glucose would be expected to change with the glucose concentration

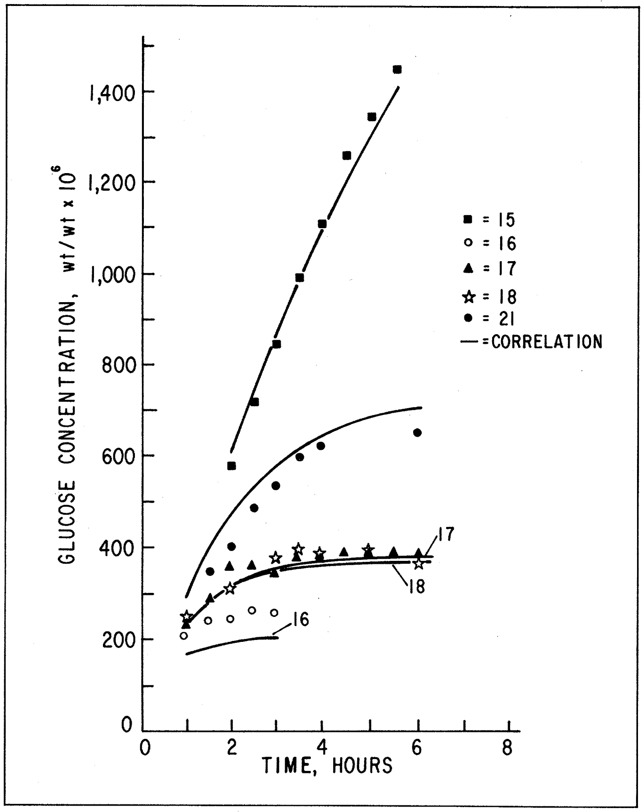

Fig. 7 Correlation of glucose concentration in precook water vs processing time for Maine Russet Burbank Potatoes, 0.95 cm French fry cuts, D = 4.057, runs 15, 16, 17, 18, 21

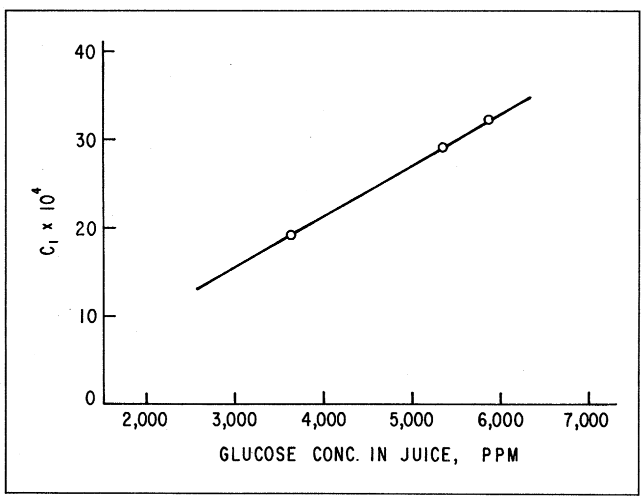

Fig. 8 Leachable solute concentration in the juice within the potato as a function of glucose concentration in the peeled raw potatoes

in the raw potato. It did. This is shown later in **Fig. 8.** We attempted to correlate the data as before with the pattern search **(Fig. 7).** The best values for C_1 and D were 0.0032 and 4.057, respectively. The model correlated runs 15, 17, and 21 within good accuracy with R equal to 0.995, 0.917, and 0.931, respectively. It failed to correlate run 16 and was poor for run 18 with an R of 0.745. Since the glucose concentration dropped is subsequent runs due to storage, we correlated runs 25 and 26 separately. These runs established values for C_1 at two reduced glucose concentrations in the raw potato with corresponding values for D of 6.693 and 0.389, respectively. Plotting the three values of C_1 *vs* glucose concentration in the raw potato juice gave a straight line

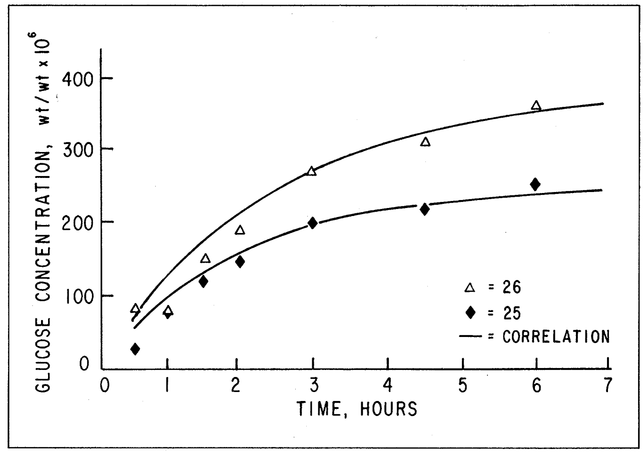

Fig. 9 Glucose concentration in precook water vs processing time for Maine Russet Burbank Potatoes, 0.95 cm French fry cuts, with C_1 correlated for each run and D correlated from previous runs, D = 4.057, runs 25, 26

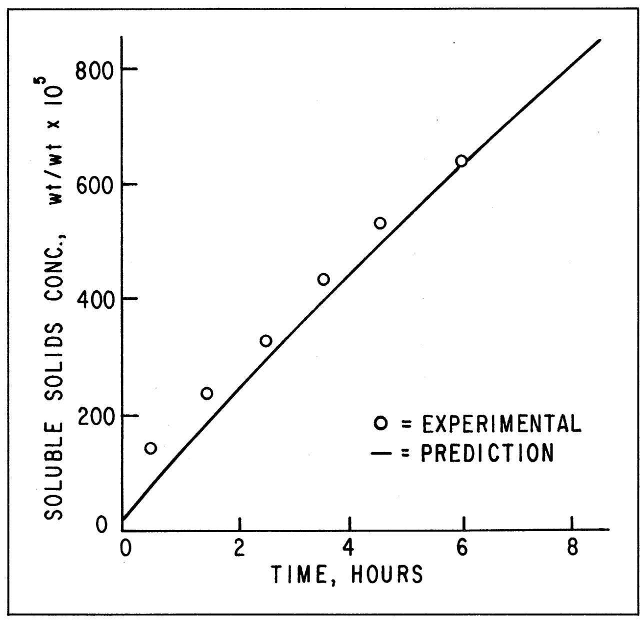

Fig. 10 Predicted concentration of soluble solids in precook water vs processing time for Maine Russet Burbank Potatoes, 1.59 cm slabs, D = 0.274

(Fig. 8). With the D of 4.057 corresponding to runs 15–21 and the C_1 values found specifically for runs 25 and 26, new curves were generated for runs 25 and 26 **(Fig. 9)** showing excellent correlation with R of 0.973 and 0.970, respectively. To apply the model to an actual process, one first would use the D for each component listed in **Tab. 2.** (Although most of our work was carried out at 77 °C, several experiments at other temperatures indicated the D did not vary significantly over the normal precook temperature range.) Then to establish the value for C_1, one would rearrange Eqn. [8] to Eqn. [9] and, using steady state process data, solve Eqn. [9] for C_1 for each solute.

$$C_1 = \frac{PMS\left[1 - \frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)\right] - W(S_1 - S)}{PM\left[1 - \frac{8}{\pi^2}\exp(-\pi^2 D\tau/L^2)\right]} \qquad \text{Eqn. [9]}$$

Once C_1 and D are known, the model can be used to study the effect of changing parameters on a process.

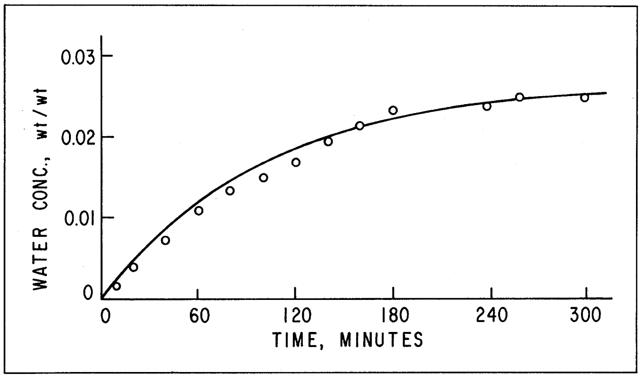

Fig. 11 Correlation of leaching data for broccoli from SWARTZ and CARROAD (4)

If the smallest nominal dimension is not 0.95 cm, the exponential term changes value because of a different $1/L^2$. We made one run using 1.59 cm slabs. We ran the process at full water recycle in which fresh potatoes were fed and withdrawn from the blanch with no change in the water, i.e., no water was added or removed from the process. **Fig. 10** shows that the model predicted the results well with R of 0.973.

To determine whether the model applies to other food products besides potatoes, we correlated the data of SWARTZ and CARROAD (4) for broccoli, R = 0.992 **(Fig. 11).** More data are needed to test the model under different operating conditions, but apparently it does apply to food products other than potatoes.

Conclusions

A mathematical model was developed to describe the leaching of soluble solids, glucose, potassium, magnesium, and phosphorus during the precooking of potatoes when diffusion is the rate controlling step. The model also applies to other vegetables. It employs nine input terms–seven independent or process variables and two constants. The seven independent variables establish the solute flow rates in the potato and water streams, piece size, leaching residence time, and blanch size. The two constants are D and C_1. The values for D at normal precook temperatures have been listed. Steady state process data are sufficient to evaluate C_1.

Acknowledgements

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Nomenclature

$\bar{C}$ = average solute concentration in the juice within the potatoes in the blanch, wt/wt
C = solute concentration in the juice within the potato leaving the blanch, wt/wt
C_e = equilibrium solute concentration in the juice within the potato, wt/wt
C_1 = initial solute concentration in the juice within the potato, wt/wt
D = diffusivity, cm^2/h
L = nominal thickness of cut pieces, cm
m = positive integer
M = potato moisture content, wt/wt
n = number of data points
P = potato flow rate, wt/h
R = multivariable correlation coefficient $(1-\Sigma(Y_i-\hat{Y}_i)^2/(\Sigma Y_i^2-(\Sigma Y_i)^2/n))^{1/2}$
S = solute concentration in the blanch water; also, solute concentration in the exit blanch water, wt/wt
S_1 = solute concentration in the inlet water to the blanch, wt/wt
V = volume of the blanch water
W = water flow rate, wt/h
Y_i = experimental point
$\hat{Y}_i$ = point on correlation curve
ϱ = density of the blanch water, wt/vol
θ = time, h
τ = extraction residence time, h

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